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UNCERTAINTIES IN LCA

Environmental assessment of air to water machines—triangulation to manage scope uncertainty

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Abstract
Purpose Devices that condense and disinfect water vapour to provide chilled drinking water in office environments, so-called 'air water generators' (AWGs), are being marketed as environmentally friendly alternatives to the traditional bottled water cooler. We sought to examine this claim.
Methods The approach adopted was a preliminary life cycle assessment with performance indicators for the use of energy and water and the emission of greenhouse gases. We compared an AWG with its main market competitor, the traditional bottled water cooler and a simple refrigerator containing a jug of water. Modelling was based on Australian conditions and energy supply. To manage possible scope uncertainty, we borrowed the idea of 'triangulation' as defined in the social sciences.
Results and discussion We found that without a renewable energy supply, the claim of environmental superiority is not supported by quantitative analysis. For each indicator, the AWG's score was typically two to four times higher than the alternatives. Energy consumption was the key issue driving all three indicators.
Conclusions Considering the principal environmental issues related to these systems, air-to-water machines significantly underperform bottled water coolers. A simple refrigerator has the capacity to perform multiple functions and therefore outperform both the bottled and atmospheric water options once allocation of burdens is considered. These conclusions are supported by all three perspectives examined to manage uncertainty.

Keywords Atmospheric water generator · Bottled water cooler · Carbon tax · Simplified life cycle assessment · Uncertainty analysis

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1 Introduction

Humankind was originally satisfied by natural surface waters, but as population pressure has grown, we have been forced to find water by increasingly energetic means. For example the city of Perth, capital of Western Australia, relied for many years on surface dams and local aquifers, at an energetic bulk water cost of 0.5 kWh/kL (Gill, 2005). Having given up the possibility of extracting groundwater 200 km away for about 1 kWh/kL because of resource competition, it is now increasingly reliant on desalination of seawater at 4.5 kWh/kL. As we spend ever more energy to find drinking water, our thoughts may logically turn to extracting water vapour from the air we breathe. Technologies for 'turning air into water' are now being mass-produced and marketed as an 'environmentally safe', 'ecologically friendly' and 'environmentally responsible' alternative to bottled water (Blackburn and Peters 2009). The aim of this article is to test these claims and to examine a means of managing the influence of scope uncertainty in a simplified life cycle assessment (LCA).

Atmospheric water generators (AWGs) typically use a small gas-compression refrigerator to chill and condense water vapour from the air. In this respect, they are identical to domestic dehumidifiers, except the condensate is chilled and disinfected to manage the risk of microbial agents for Legionnaires disease and others which might breed on a moist condenser. Many of these machines are similar in size and appearance to a bottled water cooler, and advertising material suggests they compete for the same market.

Bottled water coolers are common and typically hold a single, reusable 15 L polycarbonate bottle atop a small gas-compression refrigerator. The product has been called 'the most environmentally friendly commercial beverage' by a representative of the industry (Gentile 2007). Previous LCA studies support this claim, showing that bottled water has a lower environmental impact than most other commercial beverages (Hanssen et al. 2007), and that bulk bottled water as used in water coolers has a lower impact than other refrigerated bottled water options (Jungbluth 2006). However, the latter study suggests that the environmental impact of drinking water from water coolers is over 100 times that of tap water, so its environmental credentials depend on the selective comparison made.

To make the appropriate comparison, the function of these machines must be considered. Bottled water consumption is driven by consumers' desire for a healthy, convenient product and concerns about the taste and quality of tap water (Doria 2006). De Wolff (2007) argues that 'on the go' convenience is an underappreciated driver of the market for small bottles of water. Similarly, a key function of the bottled water cooler is that it enables self-service provision of water to staff and visitors in places where modern expectations of comfort conflict with cultural norms, which dictate that there are no taps connected to urban water mains (such as an office foyer, retail store or meeting room), or where mains water is not available (such as a construction site). In many such places, the option of a water chiller connected to a city water supply is inappropriate, despite their popularity in other institutional settings. This function is what separates bottled water coolers and AWGs from tap water and from other chilled drinking water products. A similar function could be provided by a jug of tap water in a small, common bar refrigerator.

LCA is increasingly used as a method of environmental assessment, as evidenced by recent global publication statistics (Peters 2009). From an initial focus on evaluation of the packaging, energy consumer products and automotive sectors (Horne et al. 2009) in a European and North American context, it has become a focus of research for the water and agricultural industries (e.g. Rowley and Peters 2009; Peters et al. 2010; Schulz et al. 2012). To our knowledge, this is the first time AWGs have been compared with their two most practical alternatives—the office water cooler and a small refrigerator.

Our aim is to inform a decision being made in many offices: whether to replace or change the technology being used to provide office workers with cool drinking water. We do this analysis in an Australian context. The challenge of using LCA or other scientific or quantitative approaches to make this comparison concerns how to compare three generic classes of product rather than three specific options. We use an approach to address the scientific problem of uncertainty in LCA scope by borrowing a method from the humanities.

1.1 Managing scope uncertainty with triangulation

Decision-makers are frequently faced with the conundrum of specificity versus generality. While standards call for the use of primary data for foreground systems (e.g. PAS2050 2008), it is often infeasible to obtain representative data for all possible components of such systems when performing a preliminary LCA, particularly when such systems are not owned by the analyst's employer or not yet built (Huijbregts et al. 2001). On the other hand, generalised or averaged data may avoid this problem, but mean that most systems are significantly different to the system examined in the LCA. As shown in Fig. 1, when considering future scenarios, there is usually a trade-off to be made. An analyst may favour forecasting based on accurate representation of the current situation or systems (towards the 'a' on the scale), but this entails the risk of being precise at the expense of accuracy (White and Mitchell 2003) or general relevance. Alternatively, decisions can be based on more general data (towards the 'c'), but this entails the risk that the data represents such an average scenario that it turns out to be irrelevant to the actual case.

The question is: what is the most meaningful way to inform decision-makers in the presence of this kind of uncertainty? The more significant a particular datum is to the overall result, the more valuable it is to identify multiple bases for the datum. This has been called 'triangulation' in the social sciences, where it refers to a wide range of methods for obtaining multiple perspectives. It has been defined in many ways, which range for example from using three data sources to identify health effects (an expert panel, patients and physicians (Wyrwich et al. 2007)), to interpreting educational data from the three perspectives offered by the disciplines of paediatrics, social science and child care (Copeland et al. 2012). For the present study, we used three perspectives to improve robustness of estimates of key data. Conceptually, we proposed that primary data for energy consumption (measured during use of the equipment in-situ) is the most precise way of knowing how much

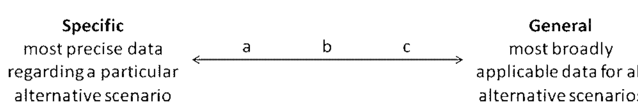

Fig. 1 Tradeoff between precision and general relevance

energy is consumed by current equipment as installed ('a' in Fig. 1) but may not be transferrable to another location nor equipment model. Another perspective is offered by claims regarding the equipment's performance as measured for rating purposes in standardised environments with new machines ('b'), which has the advantage of greater comparability between locations but the disadvantage of less accurately predicting the ensuing impacts in any actual installation. At the other extreme ('c'), a theoretical model of the equipment avoids the potential for excess specificity associated with consideration of a particular model (of AWG, water cooler or refrigerator) but is necessarily a forecast rather than an observation.

This differs from normal experimental error management, where one might (for example) use triplicate measurements from a single measuring device to estimate variability of performance, in that it is not so much the variability of a particular measured output variable that is being considered. Rather, the same data item is considered from three perspectives representing different degrees of generality of the scope of the LCA.

2 Methods

2.1 Goal and scope

The goal of this study is to help inform the many small businesses faced with selecting a non-piped water supply for staff or visitors. The study is based on the specifics of the Australian market, but the key Life Cycle Inventory (LCI) data will allow the reader to translate the results into their own region. The systems considered are an AWG, a bottled water cooler and a small refrigerator containing a jug of water filled by staff from the nearest piped water supply.

For ease of communication and comparison with other studies, the functional unit for this study is the delivery of 1 L of water chilled to 5 °C in a small office environment. All systems were examined on the basis of the provision of 5 L/day on weekdays, 52 weeks per year under air-conditioned office conditions. In our experience, this volume was adequate for the daytime needs of 15 information workers on one floor of a building, some of whom ate lunch elsewhere, and is therefore appropriate to our aim. (A higher daily water demand, which might be experienced when supplying larger officers or employees doing physical work, would support the economics of introducing a piped-water chiller.)

2.2 Life cycle inventory

A preliminary study (Blackburn and Peters 2009) identified the electricity consumption of these systems as the principal variable in determining environmental performance. Trying to identify the performance expectations of a commercially produced AWG in the absence of clear government requirements on their marketing can be difficult. As previously discussed (Blackburn and Peters 2009), different manufacturers report different types of statistics, if any, but an average value of 0.55±0.09 kWh/L was identified from duty performance claims for humid conditions (25 L/day, 27 °C, 60 % relative humidity) for three typical office-scale machines with a power rating of 500 W. Assuming the same power consumption in more typical office conditions (21 °C, 50 %) and the reduced water production associated with these conditions (16 L/day) claimed by one of the more informative manufacturers (Island Sky 2007), one may estimate an average duty (variable) energy consumption of 0.88 kWh/L. We contrast 'duty' with 'standby' power, the fixed consumption independent of the volume of water supplied. Standby power data for AWGs was unavailable, but the refrigeration requirements are presumably similar to bottled water coolers. These data are shown in Table 1.

The theoretical standby energy calculation was based on the heat of vaporisation of water (44.02 kJ/mol at 21 °C), a typical value of the refrigerator unit coefficient of performance of 1.5 for domestic dehumidifiers (Brundrett 1987), insulation of the unit with 1 cm of polyurethane foam ($k=0.04\ W.m^{-1}.K^{-1}$) and an external air film ($k/a=24\ W\ m^{-2}\ K^{-1}$) resulting in 80 kWh $year^{-1}$. Many such devices have seven filtration or sterilisation steps including initial and final UV treatment and filters of decreasing pore size ending with a reverse osmosis membrane. Such processes also demand energy: manufacturers of small scale UV sterilisation equipment often use a 40 W bulb, and we found desktop water filter energy consumption data from 0.0014 to 0.0037 kWh/L, so 0.2 kWh/L for two UV steps and a figure of 0.003 kWh/L for each of five filtration steps is reasonable. Taken together, these additional process steps were estimated to account for 0.4 kWh/L.

We performed some experiments on a Hendrix HR-77A AWG which had a rating of 550 W, similar to the sibling models described online (e.g. Global Sources 2011). We found that under typical office conditions (22 °C, 45±15 % humidity), this consumed 1.6 kWh/L. Experimental determination of the standby power produced an average of 0.49 kWh/day.

The second option assessed was the bottled water cooler. The water cooler we used and many like it have a stated rating of 49 W. They are said to produce 5 L/h at maximum capacity, so this would correspond to a duty power consumption of 0.0096 kWh/L. The office water coolers we examined were not provided with any detailed claims about energy consumption, although the USEPA has standards for standby power, suggesting 0.29 kWh/day and 0.16 kWh/day for conventional and high-efficiency water coolers, respectively (USEPA 2008). As our experiments were on a device making no claims to efficiency, we used the former value.

Table 1 Summary of operational electricity consumption

		AWG	Water cooler	Refrigerator	
Duty	claim/literature	0.88	0.0096	0.01	kWh/L
	theory	0.85	0.0124	0.01366	kWh/L
	experiment	1.56	0.0657	0.00907	kWh/L
Standby	claim/literature	106	106	228	kWh/year
	theory	80	75	210	kWh/year
	experiment	178	137	228	kWh/year
Total	claim/literature	1,250	118	243	kWh/year
	theory	1,185	91	228	kWh/year
	experiment	2,206	223	240	kWh/year

One can compare these data with thermodynamic calculations for water coolers based on the heat capacity of water: 75.3 J/K/mol. Cooling a litre from 21 to 5 °C takes 0.0124 kWh/L assuming a coefficient of performance of 1.5, consistent with the previous discussion. To estimate the potential significance of continuous losses (heat absorption), we disassembled a water cooler and estimated a standby heat loss of 0.21 kWh/day based on the geometry and standard material data.

In our experiments, the water cooler performance was 0.049 kWh/L. This higher value was expected, given that the unit is 7 years old, and the refrigeration circuit has been operating in duty or standby operation almost continuously over that period. Both the pump and motor efficiency have had time to deteriorate significantly.

The third option assessed was the small refrigerator. There is no standard definition of duty operation of an office refrigerator, but most refrigerators have been tested for power consumption under closed-door operation. The 134 L refrigerator in question was rated by the Australian Government at 376 kWh/year, at a standard ambient temperature of 32 °C, corresponding to 1.03 kWh/day (Commonwealth of Australia 2010). This represents the power consumed to remove heat entering the refrigerator via door-seals, insulated walls and the defrost cycle. We estimated the theoretical power consumption of the duty operation as the energy necessary to cool 5 L per day of water (75 J/K/mol) from 21 to 5 °C, to likewise cool 134 L of air per door opening each of ten times and to condense the associated moisture (we assume the air goes from 50 % humid at 21 °C to saturation at 5 °C, so the actual condensed water is only 0.4 g per opening, and the condensing work is insignificant). The coefficient of performance of a standard bar refrigerator is assumed to be about 1.5, consistent with the other two options. With these assumptions, the resulting duty energy demand is only 0.014 kWh/L or 18 kWh/year, so clearly the energy demand under closed door operation for 365 days of the year is more significant than the duty energy demand on weekdays—the operation is dominated by heat transfer through the refrigerator body.

Our experimental results are similar: 0.0091 kWh/L duty plus 228 kWh/year under closed-door operation. The duty power demand is thus a minor part of the total annual power demand of 240 kWh/year. The percentage difference between our closed-door performance and the official test result agrees with the difference in theoretical Carnot cycle efficiency between 32 and 21 °C to two significant figures. (Since duty power is relatively small, in the absence of a duty claim, we used the average of the theoretical and measured duty power as the claimed duty power.)

There are some consumables to consider for each option. There are external sources of drinking water for the water cooler and small refrigerator. In the latter, this was assumed to by Sydney tap water. Relevant LCI data (Lundie et al. 2005) was used to calculate the energy for this process: 0.366 Wh/L. Water treatment chemicals were not considered but would be expected to represent an increase in this figure of approximately 12 % (Lundie et al. 2004). The water cooler's water was, consistent with practice (Blackburn and Peters 2009), trucked 35 km from the aquifer used by Australia's largest supplier to Sydney, the largest city on that continent, in 15 L polycarbonate bottles. During operation, the main material flow other than water is this plastic associated with the water cooler. The bottles weigh approximately 750 g. The polycarbonate bottles are reused 30 times before recycling. The filters used in the AWG are said to last for several tens of thousands of litres, representing a relatively small material investment per litre. We therefore excluded resource demands and carbon emissions associated with them from the analysis. The other material demands of equipment maintenance were considered insignificant.

Typical construction material data for the three systems is shown in Table 2. In the case of the refrigerator, this was obtained by considering the mass of our small system and the proportions of different materials listed by Guiterrez et al. (2008) for a similarly sized system. For the water cooler and AWG manufacturers, data was augmented by visual inspection of systems. These estimates are considered approximate, but as they do not have a significant impact on the results, no further effort was applied to refine them.

Table 2 Summary of key construction material data

Material (kg/unit)	AWG	Water cooler	Small refrigerator
Cardboard packaging	3	3	3
Aluminium			2.1
Steel	35.5	6	28
Copper	3.5	3.5	0.36
HDPE	5	2.5 (no bottles)	5.3
Polyurethane insulation			6.6
Polystyrene insulation	0.08	0.08	
R134a (at sale)	0.21	0.04	0.37
Total	47	15	45.4

It is assumed that 50 % of the refrigerant is recovered for recycling at the end of the 15 year life of the refrigerant systems (Harvey 2006). The rest of the refrigerant is lost to atmosphere during operation, where it has a global warming potential of 1300 kg CO_2-equivalent/kg. It is unclear whether the other materials would be recycled or landfilled after 15 years, so end-of-life was not considered for the remaining capital equipment. This exclusion is not expected to have a significant bearing on the results in a country such as Australia that generally avoids energy recovery from solid waste.

2.3 Life cycle impact assessment

The indicators chosen for this study were water use, primary energy use and greenhouse gas emissions. The approach taken to water use here is purely volumetric because more detailed methods rely on geographical information about the origin of materials and energy (e.g. Pfister et al. 2009) which was either unavailable or similar for each of the three systems, so the volumetric information offers the best potential to compare their relative performance. Primary energy considers the ultimate source of the energy, the majority of which is coal in this study. It would be interesting to consider waste generation by the three systems. In the absence of reliable data on waste production, and considering that the key consumables in these systems are derived from petrochemical resources, primary energy (which includes the energy content of non-combusted petrochemicals) may be a proxy indicator of environmental impacts associated with resource consumption and waste (Arvidsson et al. 2012). Greenhouse gas calculations are based on the current equivalency factors and a 100 year timeframe (e.g. methane is 25 kg CO_2-equivalent/kg).

3 LCA results

Using this triangulating approach as a means to generating operational data results allows a range of results to be generated, improving the applicability of generalisations made about these three technologies. As shown in Figs. 2, 3 and 4, the results demonstrate that the AWG performs worst of the three options examined here. In this part of this article, we look at the major contributors to each result. Unless otherwise stated, the proportions described in the text are based on the median of the three results (claimed, measured and theoretical) for each office water system. The graphs are drawn using the highest and lowest estimates as error bar lines, irrespective of which of the three perspectives led to that value. (Readers interested in which was which can refer to Table 1.)

One of the most striking aspects of the results is how much ‘virtual water’ goes into the operation of the AWG, despite its unique use of atmospheric moisture as a source of drinking water. The inventory results show the AWG uses between 4 and 8 L for every litre of drinking water it provides. (This does not include the condensed water vapour.) This is a result of the power source used as 99 % of this water is a consequence of coal washing and power station cooling operations used to provide electrical power. The counterpoint is that, from a water conservation perspective, the AWG may be the most interesting option if it were entirely powered by renewable energy (discussed later in this article). The AWG water demand is two to four times higher than that made by the refrigerator or water cooler, which have approximately the same ‘water footprint’ of 2 L/L. In the case of the cooler, the largest component of the water consumption is the actual (groundwater-sourced) product (50 %), followed by water use associated with the power consumption of the cooler device (21 %) and the water bottling plant. The refrigerator has a similar breakdown of water demands: 54 % is surface water extracted for drinking water (including 8 % losses between dam and tap), and 43 % is for energy supply.

The primary energy consumption of these systems is also significantly in favour of the refrigerator or cooler over the AWG. Its average calculated energy consumption is 6.2 or 6.8 times higher than the refrigerator and cooler, respectively. In the case of the refrigerator, 95 % of the energy demand is associated with power supply to the office. For the cooler, the office still pays for the majority of the energy supply (58 %), followed by the bottling plant (25 %). Ten percent is associated with production of the polycarbonate bottles, and a surprisingly small amount (5 %) is demanded by the delivery trucks.

The predicted climate impacts of the three systems show a similar pattern to the energy results, a reflection of the small contribution made by refrigerant gases to the overall results. The AWG produces 5.9 or 7 times more greenhouse gases than the refrigerator or cooler, respectively. Power supply to the office dominates the refrigerator and AWG emissions (90 and 99 %, respectively), while refrigerant leakage results in 6 and 0.7 %, respectively. The cooler

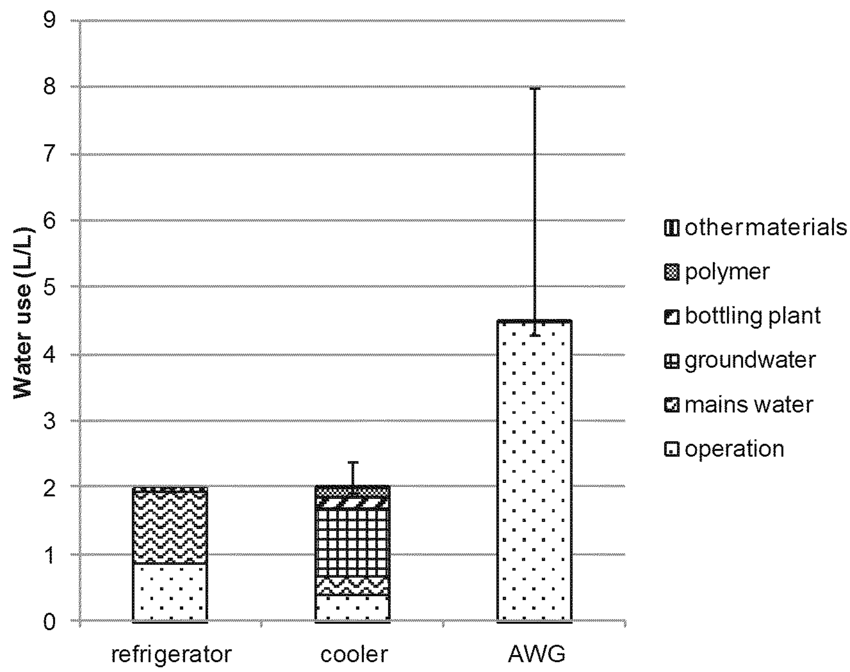

Fig. 2 Water use by three office water alternatives

results are marginally more complex with the office and bottling plant power, causing 60 and 26 % of the total results, while plastic bottle production, trucking and refrigerants cause 8, 4 and 0.9 % of the total contribution to climate change, respectively.

4 Discussion

Community concern about the greenhouse emissions associated with desalinated seawater as an alternative to surface water supplies is a key political barrier to its development, and one that has forced several democratic governments to supply desalination plants using wind power. Assuming 4.5 kWh/kL and a typical coal-based electricity supply with a greenhouse intensity of about 1 kg CO_2-equivalent/kWh, desalted seawater has a greenhouse intensity of 4.5 g CO_2-e/L. But compared with this benchmark for (bulk, non-chilled) tap water, the AWG is three orders of magnitude worse. Promoting AWGs on the basis of their environmental performance seems, therefore, to be an absurd marketing strategy that only works when buyers focus exclusively and qualitatively on the use of plastic associated with bottled water. Likewise, an ordinary bar refrigerator can easily compete for

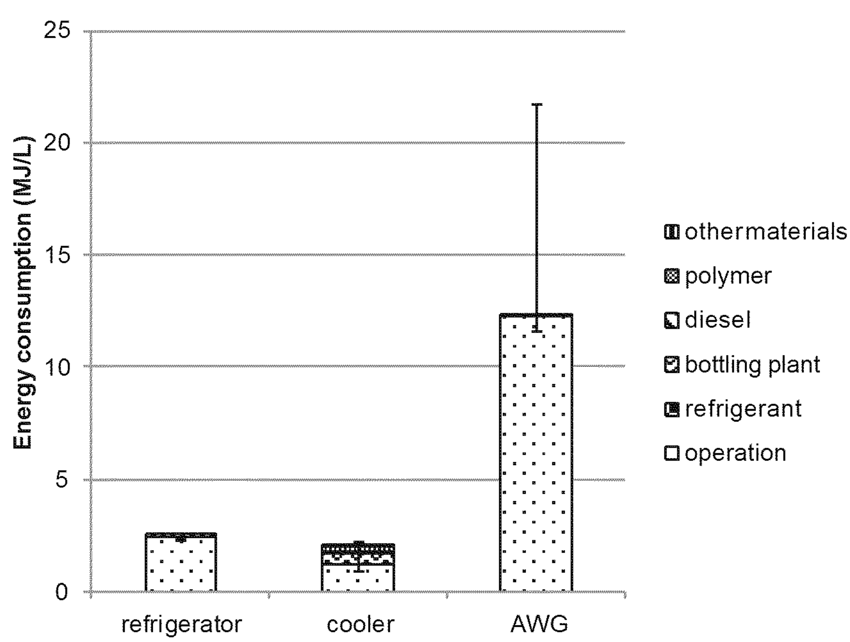

Fig. 3 Primary energy consumed by three office water alternatives

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the claim of environmental friendliness when one considers the greenhouse emissions of AWG technology. Given that 99 % of the water use and greenhouse gas emissions of the AWG are associated with the power supply to the office, the obvious way to improve this device is to supply it with wind or solar energy. In an office with such a power supply, the AWG would significantly outperform the other options with respect to the water use indicator. It would also outperform the water cooler on greenhouse emissions unless the water cooler's bottling and trucking operations were operated on a carbon neutral basis.

Many advanced economies are introducing some form of carbon tax. The UK draft energy policy has a carbon floor price of £16/t CO_2 in 2013 (DECC, 2011), which is the same order of magnitude as the typical cost of European abatement certificates (€6–32 since inception), and Australia recently introduced a cap-and-trade scheme for carbon emissions with an initially fixed price of $23/t CO_2. We use the latter as an example of such financial incentives to see what effect they might have on option selection by consumers of chilled water. Readers can use the data shown in Table 1 and Fig. 4 to compare this example with the outcome in their own jurisdictions.

Assuming the carbon price signal is transferred in full by the power generators to their customers, an incentive of between $25 and $46 per annum (for 475 kL/year, based on the functional unit in this study) will exist for businesses operating a water cooler have to avoid switching to an AWG. However, this is only part of the overall economics, which are naturally quite sensitive to energy consumption. The Hendrix HR-77 has been offered for $728/year (Rafico 2011), and at 22 cents/kWh the electricity would cost between $261/year and $485/year, while one major retailer of water coolers offers a typical model for $140/year and water at $12.70 per 15 L bottle (Neverfail 2011). Electricity for the water cooler would be between $20 and $32. This makes the water cooler the more expensive option overall by a margin of between $60 and $272. However, companies expect Australian electricity prices to increase on average by 17 % within 2 years (Reed 2011), which would make the water cooler $19 cheaper than the AWG at the highest energy consumption estimated for this article. Of course, a business that was trying hard to save money would simply find a cheap refrigerator which would cost between $50 and $53 to run and less than $3 to load with tap water.

Some policymakers prefer to avoid economic instruments for climate change intervention in favour of direct government subsidies of particular activities (e.g. Loughnane 2010). Using the data above, to have the same effect on office water supplies as the cap-and-trade scheme, a subsidy of between $3.7 and $6.8 million per annum would need to be distributed to the approximately 150,000 Australian users of water coolers to have the same marginal carbon efficiency incentive effect. It would be interesting to compare the administrative cost of approving and administering such direct subsidies with the government's preferred administration of a cap-and-trade scheme, which only directly interacts with an estimated 500 large emitters of greenhouse gases (Crabb 2011), but that is beyond the scope of this article.

5 Conclusions

While cost and other factors are relevant to any decision regarding water infrastructure (Lundie et al. 2006; Short et al. 2012), AWGs cannot be recommended on the basis of the

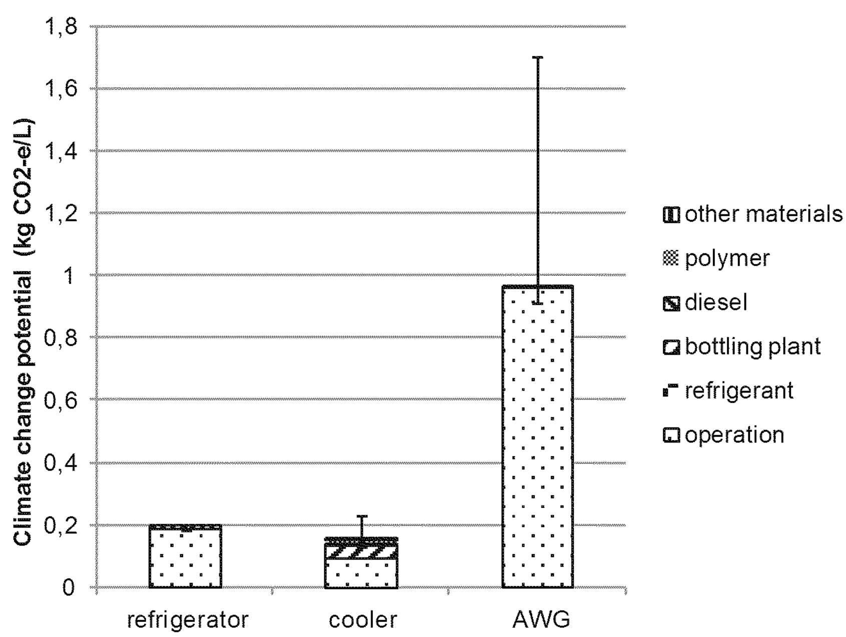

Fig. 4 Greenhouse emissions of three office water alternatives

environmental indicators in this article. On the other hand, an ordinary refrigerator seems to be the best option for the environmentally conscious office, given its potential to deliver at least two services for staff. From a physical perspective, an allocation to refrigeration of half the burdens associated with the refrigerator could be appropriate in a scenario in which 5 kg of food was kept cool besides the water. In this scenario, there would be a significant difference between the cooler and the refrigerator, with the provision of refrigerated water causing about half the burdens associated with the water cooler alternative.

In practice, the energy demands of all these systems will be higher than calculated here as the heat they expel must be removed by an office air conditioner. It is beyond the scope of this paper to estimate the additional energy that would be expended removing that heat load under seasonal weather conditions in different locations, but given the dominance of the in-office energy consumption of each option on the overall results, one would expect the differences in energy consumption and climate change potential to only become more distinct.

It has been said that 'Somewhere… between the specific that has no meaning and general that has no content, there must be… for each purpose and each level of abstraction, an optimum degree of generality' (Boulding 1956). Like many forms of predictive analysis in other fields like economics, environmental LCA has to cope with uncertainty regarding the optimal degree of generality of the input data. In this article, we have demonstrated an approach to managing this uncertainty by using measured, claimed and theoretical estimates of the key variable impacting performance. This 'triangulation' approach will not suit all LCAs because of the common difficulties in obtaining LCI data for one of the three perspectives used, but in the short term, it should be relatively applicable to the examination of household goods and transportation.

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